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Development and Integration of a Multi-Functional Spirometer for Home-Based Respiratory Monitoring and Disease Classification

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A B S T R A C T

This paper introduces a unified respiratory health monitoring device that integrates multiple key functions, including real-time airflow measurement, respiratory condition classification, and patient adherence tracking. By leveraging advancements in compact sensor technologies, machine learning, and portable device engineering, the device offers a comprehensive, affordable solution for home-based respiratory health monitoring. It can accurately analyse breathing patterns using advanced machine learning algorithms, classifying conditions such as asthma and COPD in real time. The system addresses the limitations of traditional devices by providing a user-friendly, cost-effective alternative, making continuous monitoring more accessible. Additionally, it tracks patient adherence to prescribed treatments, ensuring consistent therapy management, which is critical for chronic conditions like asthma and COPD. Designed for easy at-home use, the device reduces the need for frequent clinic visits, empowering patients to take a proactive role in their health. Its compact, portable design further enhances convenience, offering hospital-grade monitoring in a personal setting. This unified approach to respiratory care not only improves patient outcomes but also lowers healthcare costs associated with emergency visits and hospitalizations. By combining multiple functions into a single unit, it revolutionises respiratory condition management.

Keywords: Respiratory health monitoring, Machine learning algorithms, COPD diagnosis, Data analysis,MSP430, .NET platform, IoT.

1. Introduction

Respiratory diseases, such as asthma and chronic obstructive pulmonary disease (COPD), are major global health concerns, affecting millions of people worldwide and leading to high rates of morbidity and mortality. These chronic conditions require ongoing management and monitoring to prevent exacerbations and improve patient outcomes. However, traditional hospital-based monitoring systems are often insufficient for providing the continuous observation necessary for effective disease management. The lack of continuous monitoring can result in delayed interventions and suboptimal care, exacerbating the burden on both patients and healthcare systems. Home-based monitoring solutions have emerged as a promising alternative, offering the potential for continuous, real-time observation of respiratory health. However, despite the availability of some home-based respiratory monitoring devices, many existing options are either prohibitively expensive or limited in functionality, typically focusing on singular aspects such as lung capacity measurement or airflow monitoring. These limitations restrict their accessibility, particularly in resource-limited settings, where comprehensive healthcare solutions are already difficult to obtain. The challenge lies in creating an affordable, multifunctional device that can provide a comprehensive picture of respiratory health. The objective of this research is to develop such a device—one that integrates real-time airflow assessment, respiratory condition detection through advanced algorithms, and patient adherence tracking into a single, portable solution. This device is designed not only to be cost-effective and user-friendly but also to deliver accurate and reliable data that can empower both patients and healthcare providers to manage respiratory conditions more effectively, thereby filling a critical gap in current healthcare offerings.

2. Literature Survey:

Existing Devices:Modern respiratory monitoring devices, including spirometers, are essential tools in diagnosing and managing respiratory conditions like COPD, asthma, and other pulmonary disorders. However, they tend to be expensive and highly specialised. According to existing research, spirometers currently in the market are costly, limiting their accessibility, especially in developing countries like India, where many patients and healthcare facilities cannot afford them. The lack of affordable, accurate devices means that millions of patients are either underdiagnosed or left untreated, exacerbating public health challenges.

Innovations in Home Monitoring:Recent advances in IoT and portable health monitoring systems have opened new avenues for creating more accessible and affordable devices. The integration of solid-state sensors, microcontrollers like the MSP430, and wireless technologies has led to the development of compact and user-friendly spirometers. These portable devices enable patients to monitor their lung function at home, transmitting data wirelessly to healthcare providers for real-time analysis.

Machine Learning in Health Monitoring:Machine learning algorithms have the potential to enhance respiratory monitoring systems by improving the accuracy and predictive capability of these devices. Convolutional neural networks (CNNs), for instance, have shown significant promise in analysing time-series data related to breathing patterns. When integrated with portable devices, CNNs can detect subtle respiratory anomalies that may not be immediately visible through manual analysis. By utilising machine learning models in conjunction with real-time data from IoT-enabled spirometers, it becomes possible to achieve more personalised and accurate diagnoses.

3.Methodology:

1.System Design and Architecture

- **Hardware Components:**
  - **Flow Sensor Selection:** We choose a **Differential Pressure Sensor (HX710B)** to measure respiratory parameters like FVC (Forced Vital Capacity) and FEV1 (Forced Expiratory Volume in 1 second).
  - **Microcontroller Unit (MCU):** We selected an **Arduino Uno Microcontroller** to handle data acquisition, processing, and communication.
  - **Bluetooth/Wi-Fi Module:** Enable wireless transmission to a smartphone app or cloud platform by the help of **Bluetooth Module (HC-05)**
  - **Power Supply:** We incorporated a rechargeable battery for portability and continuous home use.
  - **Display Interface:** We add an OLED/LED display for immediate user feedback on respiratory metrics.
- **Software Components:**
  - **Embedded System:** We develop firmware using **JavaScript and CSS** for real-time data processing and filtering using an MCU. Algorithms for signal conditioning (removal of noise and interference) will also be implemented.
  - **Mobile Application:** We created a mobile app for users to visualise spirometry results, and communicate data to healthcare providers.
  - **Cloud Integration:** Store patient data securely in a cloud database for long-term monitoring and advanced analytics.

2. Signal Pre-Processing

- **Data Acquisition:** Spirometer signals are acquired as airflow and pressure measurements over time.
- **Signal Filtering:** We apply digital filters (e.g., low-pass or band-pass filters) to remove noise, artifacts, and external disturbances from respiratory signals. This ensures the accuracy of FEV1, FVC, and other parameters.
- **Normalisation:** Normalised the respiratory signal data to ensure uniform scaling across different recordings and users.

3. Feature Extraction

- **Respiratory Features:** Extract key respiratory features from the spirometry data:
  - **Forced Expiratory Volume (FEV1)**

$$\text{FEV1} = \frac{\text{Volume of air exhaled in first second}}{\text{Total volume exhaled}}$$

  - **Forced Vital Capacity (FVC)**

$$\text{FVC} = \text{Total volume exhaled during a forced expiration}$$

  - **Peak Expiratory Flow (PEF)**

$$\text{PEF} = \frac{\text{Maximum flow rate of air during expiration}}{\text{Time}}$$

  - **Tiffeneau Index (FEV1/FVC ratio)**

$$\text{FEV1/FVC Ratio} = \left(\frac{\text{FEV1}}{\text{FVC}}\right) \times 100$$

- **Time-Domain Analysis:** We analysed the time-based features of the respiratory cycles, such as breath duration and volume per breath.

- **Frequency-Domain Analysis:** Apply Fourier Transform to identify periodic patterns or disturbances in the signal that could indicate pathology.

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt$$

LUNG FUNCTION CLASSIFICATION	FEV1/FVC RATIO
Normal	≥ 80%
Mild Obstruction	70% - 79.99%
Moderate Obstruction	60% - 69.99%
Severe Obstruction	50% - 59.99%
Very Severe Obstruction	< 50%

Table 1: Diagnosis Conditions

4. Machine Learning for Disease Classification

- **Dataset Creation:**
  - We collected labelled respiratory data from healthy individuals and those with various respiratory conditions (e.g., asthma, COPD).
  - Data is divided into training and testing datasets, with 70% used for training the model and 30% for testing its accuracy.
- **Feature Selection:** We perform feature selection techniques like Recursive Feature Elimination to reduce the dimensionality of the data and improve model efficiency.
- **Classification Algorithms:**
  - **Support Vector Machines (SVM):** We apply SVM for binary and multi-class classification of diseases. We use Radial Basis Function (RBF) and linear kernels to handle non-linear patterns in the data.
  - **Random Forest (RF):** Use of RF for multiclass classification to differentiate between diseases like asthma, bronchitis, and COPD.
  - **K-Nearest Neighbors (KNN):** Implemented KNN to categorise the respiratory data based on similarity to known cases in the dataset.

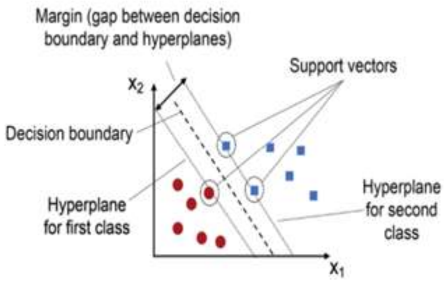

Fig. 1. A simple illustration of the Support Vector Machine (SVM) algorithm in 2-dimensions. .

5. Model Training and Evaluation

- **Training:** We use the training dataset to develop predictive models. Each model (SVM, RF, KNN) is tuned using cross-validation.
- **Testing:** We evaluate model performance on the testing dataset.

6. Validation and Testing

- **Clinical Validation:** Partnered with healthcare institutions to validate the device with real patients in home and clinical settings.
- **User Testing:** We tested the device in home environments to ensure that the spirometer is easy to use, reliable, and capable of wireless data transfer.

7. Integration and User Interface

- **Mobile App Integration:** We develop a user-friendly app to receive real-time respiratory data from the spirometer. The app offers:

- Alerts for abnormal readings
- Disease risk classification

- **Cloud-Based Data Management:** Data is stored in a secure cloud system accessible by patients and healthcare providers for ongoing monitoring.

8. Performance Evaluation

- **Accuracy Testing:** Evaluated the accuracy of respiratory measurement using the spirometer compared to standard clinical devices.
- **Usability Testing:** Conducted usability studies to assess patient comfort, ease of use, and the effectiveness of the mobile interface.
- **Data Security:** We ensure that the system complies with data privacy standards by encrypting all patient information transmitted between the spirometer, mobile app, and cloud storage.

9. Final Integration and Feedback Loop

- **Iterative Development:** Incorporated feedback from users and clinicians to improve device design, data accuracy, and disease classification algorithms.
- **Updates and Maintenance:** We roll out firmware and software updates as necessary to refine the classification models and enhance user experience.

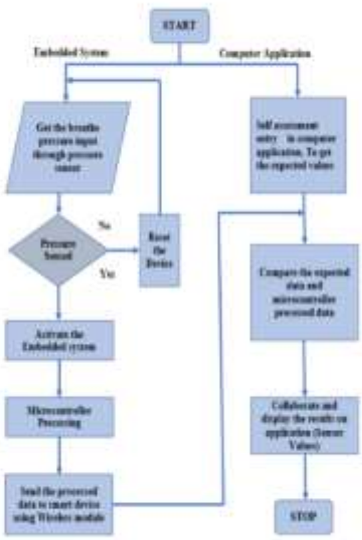

Fig 2: Methodology Flowchart

4. Results and Conclusion:

This innovative multi-functional spirometer brings a new level of accessibility and convenience to respiratory health monitoring. By combining advanced sensor technology and machine learning, it empowers individuals to manage chronic conditions like asthma and COPD from the comfort of their homes. Unlike traditional, expensive devices, this affordable solution allows for real-time tracking of respiratory health, making it easier for patients to stay on top of their treatment and avoid hospital visits.

The device not only simplifies the process of monitoring lung function but also provides actionable insights, helping both patients and healthcare providers make better decisions. This technology is especially valuable in regions with limited access to healthcare facilities, enabling early intervention and ultimately improving the quality of life for those living with chronic respiratory conditions.

By turning complex medical monitoring into a user-friendly experience, this project paves the way for more patient-centred healthcare, where people can take charge of their health, stay informed, and live healthier lives.

Fig. 3.display of patient details on GUI

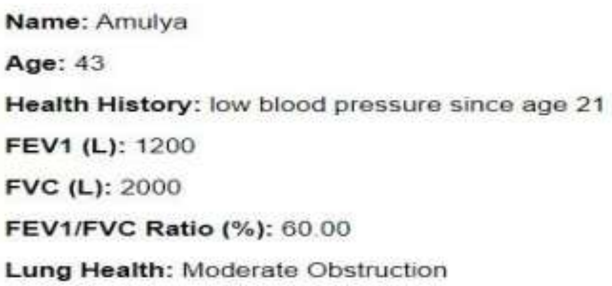

Fig. 4. patient details and diagnosis

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